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TR 77047

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ROYAL AIRCRAFT ESTABLISHMENT

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9 Technical Report 77047

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10 D.W.S. Lodge BSc., MSc.

11 Mar 77

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12 39p.

Procurement Executive, Ministry of Defence
Farnborough, Hants

UNLIMITED

310 450

UDC 629.195 : 533.6.013.7 : 620.179.14 : 537.612.2 : 537.621.5

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Received for printing 31 March 1977

THE MAGNETIC TESTING OF THE UK5 SPACECRAFT

by

D. W. S. Lodge, BSc, MSc

SUMMARY

UK5 arrived for magnetic testing with an unexpected and excessive magnetic moment. The source of the moment was identified as the counter bodies of experiments B and D. This Report describes the work carried out to bring the moment within its specified limits. A great deal of unprogrammed activity was required to do so including the development of tests to confirm the eventual magnetic stability of the spacecraft. In particular, unscheduled and detailed magnetic testing was carried out at the launch site under highly adverse conditions.

Departmental Reference: Space 524

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1 INTRODUCTION

UK5[1], re-named Ariel 5[2] after launch, is a spin stablized spacecraft carrying six experiments to investigate the position and energy spectra of X-ray sources in space and the diffuse X-ray background. It had the design requirement that the spin axis drift should not exceed 0.1° per orbit.

A major disturbing torque acting on a spacecraft in a near earth orbit can be that due to the interaction between the magnetic dipole moment of the spacecraft and the magnetic field of the earth. This moment is due to the permanent, induced and stray magnetism[3,4] of the spacecraft. Permanent magnetism is that property of ferromagnetic materials by which, when placed in a magnetic field, they themselves become sources of magnetic field and they continue to be such sources when the external field is removed. The magnetism is permanent in the sense that it exists in the absence of an external field; it is not permanent in the sense that it cannot be changed. In fact, as will be shown subsequently, control can most easily be exercised over the permanent magnetic moment. Induced magnetism is also a property of ferromagnetic materials by which, when placed in a magnetic field, they become sources of magnetic field, but they cease to be so when the external field is removed. Stray magnetism refers to the magnetic field generated by current loops within the spacecraft. Obviously, it only exists when experiments or sub-systems are turned on, but it will change according to the particular mode of spacecraft activity that is selected.

The purpose of the magnetic testing was to measure and where necessary to modify the spacecraft magnetic moment to ensure that the magnetic disturbance torque would be compatible with the spin axis drift rate requirement. The spacecraft Magnetic Code of Practice called for the net permanent and stray magnetic moment to have a component along the spin axis of less than 0.06 μWb m. Fig 1 shows the spacecraft system of axes, with the spin axis being the z axis. Components normal to the spin axis were less significant since, as the spacecraft experiences a changing magnetic field due to its orbital motion at a rate slow compared with its spin rate, any torque due to those components effectively cancel out over one revolution of the spacecraft. However, they cannot be too great or they will cause perturbations. Therefore the design aim was for a maximum total permanent and stray magnetic moment of 0.25 μWb m.

The magnitude of the induced magnetic moment is not of major importance;
047 however, it is important that the moment be reasonably symmetrical. If there is a particular orientation of the spacecraft relative to the magnetic field which

maximizes the induced moment, then that will be a preferred orientation and will give rise to a restoring torque if the attitude is changed.

The greatest amount of control over the magnetic moments of a spacecraft lies with its designers. They should avoid ferromagnetic materials wherever possible and design cable runs, particularly those carrying heavy currents, so that loops are avoided and twisted pairs used for forward and return currents. However, the spacecraft is magnetically tested so that remedial action can be taken to overcome the legacy of unavoidable (or otherwise) departures from those desired aims. The permanent moment can be reduced by demagnetization, that is exposure to a gradually reducing alternating magnetic field. UK5 had provision for the addition of small Mumetal strips to make the induced moment symmetrical. There was also a small permanent magnet which could be set in magnitude and direction to cancel any residual permanent moment and the stray moment. Finally, UK5 carried a dipole correction magnet-torquer (DCM). This was a permanent magnet whose axis of magnetization was along the spin axis. An appropriate coil and power supplies enabled the level of magnetization to be set and reset as necessary, by ground command, to provide final in-orbit trimming of the spacecraft moment and to compensate for post launch magnetic changes. It could also provide a limited degree of attitude control.

This Report describes how the magnetic properties of UK5 were measured and the steps taken to reduce the permanent moment to within the design limits. It includes the unscheduled activities which proved necessary after the initial tests showed major magnetic anomalies on board. The test programme at the RAE was extended from 4 days to 6 weeks and further major tests were carried out at the launch site.

2 SPACECRAFT TESTS AND RESULTS AT RAE

The RAE magnetic test facility and the test procedure are described in Appendix A.

The history of the magnetic moments of UK5 measured during the course of the tests is given in Table 1. The spacecraft arrived at the RAE with the unexpectedly high permanent magnetic moment of 76 μWb m. Exposure to a 2000 A/m magnetizing field along the direction defined by the total permanent magnetic moment vector had a negligible effect. This test demonstrated that the level of magnetization was the result of exposure to an effective field of greater than 2000 A/m, which is about 50 times greater than the ambient magnetic field intensity. Three attempts were made to demagnetize the spacecraft using an

exponentially decreasing alternating field. In each case the highest normally attainable initial peak field of 4000 A/m and a decrement of 1% per cycle were used. The frequency however was reduced from 2 Hz at the first attempt to 0.5 Hz and 0.1 Hz for the second and third attempts respectively. The frequency reduction was to overcome any shielding of the magnetic components by conducting screens. By this means the permanent moment was reduced to 28 μWb m. As this value was two orders of magnitude greater than the specified upper limit it was clear that extra, unscheduled tests were required.

Examination of the spacecraft with a hand held magnetic probe suggested that experiments B and D were the major magnetic sources. This was confirmed after their removal left the spacecraft with a permanent magnetic moment of 1.4 μWb m. A further demagnetization reduced this to 0.32 μWb m. The subsequent history of experiments B and D is described in the next section. However, they were eventually partially demagnetized and temporarily fitted with their own Alcomax III compensating magnets. A feasibility check established that the spacecraft compensating magnet could be used to bring the permanent moment within 0.25 μWb m and the induced moments were measured. Permanent holders were installed for the experiment compensating magnets, the spacecraft compensating magnet was removed and a baseline measurement of the spacecraft permanent moment was made. UK5 was then removed from the facility for tests elsewhere pending final magnetic testing before shipment to the launch site.

When the spacecraft returned, the permanent moment was not significantly different from the baseline measurement either in magnitude or direction. This result demonstrated that its magnetic properties were sufficiently stable to be unaffected by the activities it had undergone in the meantime. Those activities included, apart from the transportation between Farnborough and Portsmouth, being powered in a variety of modes and operating the DCM.

The stray magnetic moment was measured and found not to change significantly during normal operation. It was also found, fortuitously, almost exactly to cancel the residual permanent moment. This rendered the spacecraft compensating magnet superfluous, though it was retained, aligned with the z axis, in a demagnetized state to maintain the integrity of the spin balance checks. The operation of the DCM was checked, though to save time at the RAE a final calibration check was later carried out at the launch site.

It was agreed with the Project Officer and the design authorities that the
047 induced moments, shown in Table 1, were acceptably symmetrical and no attempt
was made to improve the situation by adding Mumetal strips.

During the latter stages of the magnetic testing at RAE, the methods and procedures by which tests could be carried out on the launch platform were being devised. The lack of time before shipment did not permit rehearsal of all the techniques in the test facility. However, a rehearsal of a crude field check, where the spacecraft was suspended from an overhead hoist, was carried out and shown to provide useful results. This test was intended to be carried out immediately the spacecraft was unpacked on the launch platform.

UK5 left the RAE magnetic test facility with a measured permanent moment of 0.29 μWb m and an estimated total moment when powered up of 0.08 μWb m of which +0.04 μWb m was the z axis component.

3 INVESTIGATION OF EXPERIMENTS B AND D

With the experiments removed it was apparent that the X-ray counter bodies, which were similar for both experiments, were the source of the magnetic moment. Subsequent identification of the characteristics of the FV 520B stainless steel from which they were made confirmed that their behaviour was consistent with the properties of that material.

The magnetic histories for the experiment B and D flight models are given in Tables 2 and 4 respectively. On removal from the spacecraft experiment B had a permanent moment of 20.8 μWb m and experiment D had one of 14.5 μWb m. The flight spare units had permanent moments of 63.1 μWb m for B and 43.8 μWb m for D. Their magnetic histories are given in Tables 3 and 5 respectively. The difference between the flight models and the spares is almost certainly due to the demagnetizing attempts the flight models experienced on the spacecraft. It is worth noting that the ratio of the permanent moment of the flight model to that of the spare is the same for both experiments. At the time to which these figures refer, the flight model experiments had been treated simultaneously and identically in the magnetic test facility. Therefore this result indicated that all four experiments had been magnetized in an identical manner.

Several attempts were made to demagnetize experiment B flight model using an initial peak field of 4000 A/m. As shown in Table 2, no useful reduction in magnetization was obtained. Experiment D flight model did not respond to a normal demagnetization at all, as can be seen in Table 4.

The demagnetizing facility was modified to use a different, smaller pair of coils which allowed the generation of demagnetizing fields with an initial peak value of up to 12000 A/m. This was at the expense of a large constant

ripple current producing a peak field of about 400 A/m which prevented a smooth decay of the demagnetizing field at low values. Using this equipment the flight models were demagnetized using an initial peak field of 8000 A/m. Tables 2 and 4 show that the magnetic moment of each experiment was significantly reduced. Experiment B flight model was demagnetized using an initial peak field of 12000 A/m and the moment was further reduced. However, further attempts to demagnetize using 12000 A/m produced an increase in the permanent moment. The results are shown in Table 2. Further demagnetizations of experiment D flight model using an initial peak field of 8000 A/m did not produce any significant change. The results are shown in Table 4. The moment of experiment D increased after successive demagnetization attempts most probably because of the unpredictable effect of the ripple current. However, the decision had already been made to fit compensating magnets, so, as the permanent moments were within the range of the magnets to be used, the experiments were removed from the facility to Portsmouth for other tests.

The magnetization of these two experiments and the magnetic properties of the material from which they were made suggested that total demagnetization could be achieved with an initial peak field of 40000 A/m. This was not readily achievable using the low frequency power supplies, but could have been produced using 50 Hz power supplies. There were two major reasons why no attempt was made. There would have been a significant risk of damage to the experiments by a field of that magnitude. There would also have been a significant risk of damage through inductive heating at 50 Hz.

The fact that the experiments were removed from the facility is recorded because on their return, the permanent moment of experiment D was observed to have doubled. Neither experiment had a compensation magnet fitted. The experiments had, as far as could be ascertained, had identical treatment away from the facility. Examination of the facility log and data showed that the only difference as far as could be checked was that experiment D had up until then only been demagnetized from 8000 A/m whereas experiment B had experienced 12000 A/m. Although it is conceivable that somehow the lower demagnetizing field could have left experiment D in a less stable magnetic state than experiment B, this was not considered likely. Careful examination of the data records virtually eliminated the possibility of an instrument malfunction or an operator error by setting an instrument to an incorrect sensitivity. Either of these possibilities
047 would have required a simultaneous error affecting four independent instruments, on two separate occasions. The recording of the magnetometer outputs was by

hard copy printer, eliminating transcription errors. Finally, equipment failure or setting to an incorrect sensitivity would affect all three axes of measurement in exactly the same way, and this did not occur. No satisfactory explanation was discovered. There was also a suspicion that the z axis moment of experiment D had reversed its polarity, but as polarity had not until the tests on return been recorded, this was never confirmed.

Although the question of magnetic stability had already been raised, the experiment D glitch made a stability investigation of the utmost importance. How this was done is described in the next section.

Experiments B and D were eventually refitted to the spacecraft, after having compensating magnets permanently affixed, with total permanent moments of 0.08 and 0.25 μWb m respectively.

All the evidence suggested that the experiments had been magnetized by exposure to a field of the order of 25000 A/m. This would have occurred during vibration testing. Both flight and spare model of each experiment had been vibration tested for flight acceptance on the same equipment. This accounts for the correlation between the flight and spare models apparent in Tables 2 to 5, as the fields experienced would have magnetically saturated the counters.

As a final precaution, the flight spares were remeasured at San Marco 7 days before launch, that is about 7 weeks after they were measured at the RAE. Only a rough check was possible with an accuracy of about ±0.15 μWb m. There was no detectable change in the permanent moment of either experiment.

4 ASSESSMENT OF MAGNETIC STABILITY

The properties of the stainless steel from which the counter bodies were made were such that whatever level of magnetization they had, that level could be confidently expected to remain unchanged under the influence of the environmental effects to be experienced by the spacecraft. Informal consultations with the Permanent Magnet Association supported this view. Nevertheless, the unexplained behaviour of experiment D and the disastrous implications for the spacecraft if major magnetic changes occurred made it essential that more evidence for stability was gathered.

The first stability tests were carried out on experiment D. It was demagnetized from 12000 A/m and fitted with a compensating magnet. The experiment was then dismantled, re-assembled and exposed to a 240 A/m steady field in each axis. The overall permanent moment was unchanged.

There were four spare counters available of the type used in experiments B and D. These were made available for a more thorough investigation. Counter No.1 had an initial permanent moment of 2.7 μWb m. A normal facility demagnetization using an initial peak field of 4000 A/m at 2 Hz decaying in peak amplitude by 1% per cycle reduced the moment to 2.0 μWb m. A second demagnetization from an initial peak field of 8000 A/m at 0.5 Hz decaying by 8 A/m per cycle further reduced the moment to 1.1 μWb m. This treatment, and the response to it, was similar to that experienced by experiment D before its anomalous behaviour. The induced moment of the counter was measured twice in 16 A/m. It was subjected to rotating fields of 40 A/m at 120 rev/min for 3 min and 12 rev/min for 10 min to simulate the spacecraft spin rates during injection and in orbit. The counter was given 50 taps with a block of wood. A 2.5 μWb m magnet was held 50 cm from and parallel to the counter body. The tap test was repeated with the magnet in that position. After each of these activities the permanent moment of the counter remained unchanged. The 2.5 μWb m magnet was placed lengthways directly on the counter body and removed. This caused a reduction from 1.1 μWb m to 0.8 μWb m in the permanent moment. A repeat of the experiment reduced it still further to 0.7 μWb m.

Counters 2, 3 and 4 were demagnetized using the normal facility method, with an initial peak field of 4000 A/m, decaying at 1% per cycle at a frequency of 2 Hz. This had the effect of increasing the moments of counters 2 and 3 from 0.07 μWb m to 0.30 μWb m and from 0.08 μWb m to 0.34 μWb m respectively. Counter 4 remained unchanged at 0.41 μWb m. Compensating magnets were fitted to counters 1 and 3. All four counters were then vibration tested using a special vibration tester designed to greatly reduce the level of magnetic field, due to the tester, to which the test object was subjected. Unfortunately, this tester was not situated at RAE and it was not possible to measure what field was actually being produced. After being vibrated, counter 3 was sent directly to Leicester University, who were the designers of experiments B and D. The remaining counters were returned to RAE. The permanent moments had changed from 0.35 μWb m to 0.29 μWb m for counter 1, 0.31 μWb m to 0.30 μWb m for counter 2 and 0.41 μWb m to 0.35 μWb m for counter 4.

Counter 2 was exposed to a succession of gradually increasing magnetizing fields and the residual permanent moment was measured after each step. The resulting magnetization curve is shown in Fig 2. It confirms that the magneti-
047 zing field needed to saturate the materials, and therefore the initial field needed for complete demagnetization is in excess of 25000 A/m. The curve also

shows that no significant change in the moment of a demagnetized counter would result from exposure to less than 400 A/m. A dramatic change would result from exposure to fields greater than about 800 A/m.

The results generally, both the magnetization curve and the more qualitative empirical tests, strongly indicated that further changes to the magnetization of experiments B and D were unlikely. They provided no explanation for the single anomalous event associated with experiment D.

5 MAGNETIC TESTING OF FLIGHT SPARES

The Magnetic Code of Practice only called for the flight spare experiments and subsystems to be demagnetized in bulk. However, in view of the problems encountered with experiments B and D, it was decided to examine each unit individually. In the event, no further excessive magnetization levels were encountered. Data handling boxes 1 and 2, the power supply monitoring unit, the power regulation and distribution unit and experiments A and C had as received permanent moments of about 0.2 μWb m. After demagnetization, using the normal method of an initial peak field of 4000 A/m alternating at 2 Hz and decaying by 1% per cycle, no item had a permanent moment greater than 0.1 μWb m.

6 SPACECRAFT TESTS AND RESULTS AT SAN MARCO

The test methods and procedures that were used on the San Marco launch platform are described in Appendix B.

At the earliest opportunity after the arrival of the spacecraft on San Marco, that was the day after, a crude field check was carried out. This involved measuring the permanent moment with the spacecraft suspended from an overhead hoist in the clean room. The test confirmed that there had been no gross change since the measurements at RAE.

A magnetic survey of the San Marco platform was carried out and is described in detail in Appendix C. It demonstrated that there were regions where the Earth's field was sufficiently uniform and undistorted by the steel platform and superstructure to enable a more accurate measurement of the spacecraft magnetic fields to be made on the deck.

The magnetic field along each spacecraft semi-axis was measured at ranges of 1.50 m for the x and y axes, 1.73 m for the +z axis and 1.25 m for the -z axis. The range in each case was from the magnetometer probe to the spacecraft centre of mass. The polar plots of the spacecraft magnetic field obtained at the RAE by rotating it and recording the magnetometer outputs had indicated

strong non-dipolar components in the permanent moment. Therefore, no attempt was made to estimate the permanent moment directly from the San Marco data. Instead, the data obtained at RAE corresponding to each axis were suitably corrected for the range change and compared with the San Marco data. The results indicated a dipolar change in the z axis moment of $+0.25 \pm 0.13$ μWb m. The x and y axes moments were unchanged within the measurement tolerance.

The magnetic moment of the spacecraft as measured at RAE was based on measurements made 2.715 m from the centre of mass. The errors resulting from the non-dipolar components of the permanent moment diminish with increasing measurement range. However, measurements were also made at the RAE at a range of 1.710 m, and it was these results which were used for comparison with the San Marco data. Table 6 shows the results.

The tolerance on the San Marco result arises as follows:-

Measurement accuracy		±2 gammas
Range measurement ±2 cm	≡	±1 gamma
Induced moment uncertainty ±0.04 μWb m	≡	±2 gammas
Calibration error		±2 gammas
Worst case		±7 gammas
Root sum of squares		±4 gammas

The RAE measurements are accurate to better than ±1 gamma.

$$1 \text{ gamma} = \frac{10^{-2}}{4\pi} \text{ A/m} .$$

Having established that a change had taken place, there was no evidence to suggest why that had happened. There were at least two obvious possibilities. First, the effects of the journey could have caused a change. Although the stability checks carried out at the RAE made this appear unlikely, there was still the unexplained behaviour of experiment D to support it. Secondly, there was the possibility of ageing effects from the magnetic components. This was perhaps the more likely, but not necessarily most reassuring, explanation, since by that time the spacecraft contained two experiments with highly magnetic counter bodies and three Alcomax III compensating magnets, all set at various states ranging from fully saturated to almost completely demagnetized. In either case, circumstances did not permit the investigation that would have been
047 necessary to determine if the change indicated a steady drift, a continuous

trend towards some asymptotic value, a value in a series of random jumps, a once and for all change or a measurement error and no change at all.

The worst case would have been a steady drift, which if continued at the rate indicated, would have exceeded the ability of the DCM to cope with it in about 9 months. It was decided that the best action was to change the z axis permanent moment, using the compensating magnet, ideally by $-0.38\,^{+0.06}_{-0}$ μWb m. In the event of a steady drift the useful life of the spacecraft would be extended by about 2 months. If any of the other possibilities was the case, the DCM would be operating nearer the centre of its dynamic range than would otherwise have been the case, and hence be more suited to dealing with subsequent changes. Fig 3 shows the DCM characteristic, and it can be seen that it is asymmetrical. Although that figure relates to a measurement made in San Marco, the results were identical with those obtained at the RAE and from bench tests.

Accordingly, the spacecraft compensating magnet, previously set at +0.09 μWb m, was removed and replaced with one set at -0.25 μWb m.

The final series of magnetic tests carried out on UK5 was a crude survey of the magnetic field near the spacecraft using a hand held probe after the compensating magnet had been changed. This survey was repeated 4 days later after the spacecraft had been mated to the launch vehicle at the last possible time before the heat shield was fitted, 7 days before the launch. It confirmed that mating had produced no gross changes.

7 CONCLUSIONS

When UK5 was launched, it was within its specified magnetic limits; there were good grounds for believing that the spacecraft would remain so throughout its design life.

The above statements, while factually correct, represent only one, albeit important, aspect of the lessons of this investigation. In the first place, although there were undoubtedly very good reasons for believing the magnetic state of UK5 was stable, there was evidence to the contrary and the decision to launch included an element of risk. Secondly, the magnetic problems were avoidable. This Report is not the place to offer any opinion on how they could have been avoided, other than to state that the counter body material was changed during the history of the spacecraft and the characteristics of the stainless steel eventually used were known and immediately suggested problems of the type that arose. It seems that those with the knowledge failed to appreciate its

significance while those who could have appreciated the problems were not aware of their existence until too late.

The magnetization of the counter bodies undoubtedly arose as a result of exposure to the approximately 25000 A/m magnetizing field produced during flight acceptance vibration testing of the units. If ever similar materials have to be used on a spacecraft, one hopes that some effort is expended on devising a way of vibration testing without simultaneously producing a field greater than the maximum steady field specified for magnetic testing, usually 2000 A/m.

Finally, some aspects of this series of tests call into question the suitability of the method of magnetic testing normally used. While entirely adequate for the testing of spacecraft which are essentially non-magnetic and with such magnetic contribution as exists being fairly dipolar, the magnetic moment cannot in practice be accurately extracted from the non-dipolar field patterns such as those eventually displayed by UK5. The most suitable method of measuring the moment directly is to measure the torque on the spacecraft when it is suspended in a known magnetic field. In practice, this technique has been very little used as the problems involved are substantial. The realistic solution to the problem seems to be to build nominally non-magnetic spacecraft from non-magnetic materials. This type of magnetic test facility is then admirably suitable to carry out the necessary checks on small fields.

Appendix A

TEST FACILITY AND METHOD AT RAE

A.1 The magnetic test facility

The magnetic test facility, whose layout is shown diagrammatically in Fig 4, consists of two areas housed in a non-magnetic building. A non-magnetic corridor links the facility to a conventional building housing the power supplies, workshop, offices and storage areas. The main test area is approximately 15.5 m long by 7 m wide by 6.5 m high with its long axis aligned towards magnetic north. The northern end contains the magnetizing and demagnetizing facility. That consists of a Helmholtz pair of coils, 3 m square. The spacing between the coils of nominally 1.8 m can be varied by ±0.3 m. Two orthogonal Helmholtz pairs of coils enclose the main coils and are used to cancel the Earth's magnetic field over a 1.5 m spherical test volume at the centre of the main coils system. These magnetizing and demagnetizing coils can be used to establish an up to 2000 A/m steady field at the centre of the test volume or a field varying sinuisoidally between 0.1 and 5.0 Hz up to 4000 A/m peak. The field amplitude can be varied manually or automatically by way of a paper tape reader. The tape reader is normally used to generate a programmed demagnetizing cycle. For UK5, tapes were available to provide an exponential decay for the peak amplitude of an alternating field of between 1 to 10% per cycle. The minimum field which can be established is 40 mA/m.

The southern end of the main area contains the three orthogonal Helmholtz pairs of coils, each approximately 6 m square, which comprise the main coil system for the controlled magnetic environment facility. These coils can be used to establish a high homogeneity and high stability magnetic field over a 1.5 m spherical test volume at the centre of the system. The field at the centre of the test volume may be set to any value within the range 0 to 48 A/m, with a resolution of ±4.8 mA/m, in any direction. The height of the test volume is the same as for the magnetizing and demagnetizing facility. The field is stable to within ±0.8 mA/m. A 1:5.5 scale replica of the main coil system stands about 9 m centre to centre east of the main coils to provide an ambient reference for the magnetometer differential probes. A second similar trio of small coils about 17 m from the main coils in a separate non-magnetic building has a triaxial magnetometer at its centre which is used to control the main coil currents to
047 compensate for variations of the local ambient magnetic field. The power supplies used to set up a zero field are independent of those used to set up an

artificial field. The zero field power supplies are connected to the main and both miniature coils in series. The artificial field power supplies are connected to the main and ambient reference coils only. By this means, the stability of the total field in the test volume is maintained when an artificial field is created, by using both power supplies simultaneously. A programme generator acting on the artificial field power supplies permits alternating or rotating fields to be established at from 0.01 to 10 Hz.

A non-magnetic trolley runs between the magnetizing and demagnetizing facility and the controlled magnetic environment facility. The mounting fixture of the trolley on which the spacecraft was placed was such that the centre of the spacecraft coincided with the centre of the test volumes and was rotatable about two axes.

The instrumentation and controls associated with the facility and the ambient reference coils already described are located in an 11.8 m long by 7 m wide by 3.5 m high ancillary area next to the main test area. The layout of the magnetometer probes was as shown in Fig 4. The magnetometer output associated with each probe pair was the difference between the fields at the measurement probe and the ambient reference probe. This method overcomes the problem which would otherwise occur as the coil currents varied to compensate for fluctuations in the Earth's field. These variations would produce a changing magnetic field outside the test volume, where the measurement probes were situated. The magnetometers used were three Forster Instruments type 1.107 and a type 1.104. The output of each was recorded on a chart recorder and simultaneously drove a digital display. The contents of the digital display were recorded as required by means of a printer.

A.2 The test method

Unless actually required for use, the magnetizing and demagnetizing facility power supplies and the associated Earth's field compensation power supplies were normally turned off. The centre of that system was then designated the reference position. The test position was the centre of the controlled magnetic environment facility.

To measure the permanent field of the spacecraft, a zero field was established at the test position. The magnetometer outputs were adjusted to zero with the spacecraft at the reference position. The spacecraft was then brought to the test position with its axis under test aligned to the west.

The magnetometer outputs were recorded by the printer, and if required by chart recorder as the spacecraft was rotated about its vertical axis. The trolley gimbal incorporated a means for marking the resulting trace at 10° intervals. This process was repeated for each axis.

To measure the induced field, an east-west field of 16 A/m was established at the test position. As before, the magnetometer outputs were corrected to zero before the spacecraft was moved from the reference position. The magnetometer outputs were recorded using the printer, with each axis in turn aligned to the west. The procedure was repeated with north-south and vertical fields of 16 A/m set at the test position.

To measure the stray magnetic field, the spacecraft was placed at the test position, in zero field and unpowered. The magnetometer outputs were adjusted to read zero, with the spacecraft axis under test aligned to the west. The magnetometer outputs were recorded as the spacecraft was powered in the required modes. The test was repeated for each spacecraft axis.

Before magnetizing or demagnetizing, the spacecraft was placed at the test position and given the required orientation. The Earth's field compensation was turned on to crudely cancel the ambient field at the reference position. The controls for the magnetizing and demagnetizing facility were set and verified before the spacecraft was taken to the reference position. The magnetizing or demagnetizing field was then applied. Demagnetization of the spacecraft was normally carried out along each of the three axes.

A.3 The derivation of the results

The parameter measured was the magnetic field produced by the spacecraft at a defined distance. Ideally, that distance should have been very large in relation to the spacecraft dimensions. The dipolar contributions to the magnetic field would then have predominated. In practice, the resolution of the magnetometers limited the measurement distance to about five spacecraft radii. Under normal circumstances this separation would have been adequate; but as discussed in the main text of this Report, for UK5, non-dipolar contributions were much in evidence during the last stages of the tests.

The technique used to derive the magnetic moment from the measured field was to treat the spacecraft as a dipole source. This has been the standard
047 technique for magnetic testing at RAE[5], at ESTEC[6,7] and in the USA[8] for some
time. Errors arising from the indeterminancy of the location of the dipole along

the axis of measurement can be corrected for by analysis of the field levels measured on either side of the spacecraft. The error due to the moment being located in a plane normal to the axis of measurement is less than 1%. The errors due to the finite field produced by the spacecraft on the measurement probes when at the reference position and on the ambient reference probes when at the test position have been neglected, since for the magnetic moments of interest, those fields are well below the detection level of the magnetometers.

The major sources of measurement error excluding non-dipolar effects are the measurement accuracy and calibration accuracy of the magnetometers. These each produce a contribution of ±0.2 gamma which corresponds to a total error of ±0.05 μWb m. It should be noted that the magnetometers are calibrated in oersteds and 1 gamma is 10^{-5} oersted which is equivalent to $10^{-2}/4\pi$ A/m. The measurement range was accurate to about ±1 mm and produces a negligible error contribution.

A technique has been developed[9] which promises to be more suitable for spacecraft of the UK5 type with multiple discrete magnetic sources. It could be used at the RAE facility, but it is not suitable for the presentation of immediate results, as has been required by past and current UK space projects. Considerable computer analysis would be required.

Appendix B

TEST METHODS AT SAN MARCO

B.1 Main tests

The technique used to measure the magnetic field of the spacecraft on the launch platform was substantially similar to that used at the RAE. However, the surroundings were somewhat less conducive to making precise and reliable measurements on a delicate spacecraft. The tests had to be conducted on the deck in the open air. The spacecraft was wrapped in black plastic sheet to provide protection from the weather, but the prospect of rain was viewed with some trepidation. Furthermore, the strong wind which blew constantly caused unwelcome motion of the magnetometer probe supports. Unfortunately, the early morning, when the wind was lightest, was the period of maximum likelihood of rain. It is perhaps unnecessary to add that rain on the morning of the tests delayed the start until the wind had reached its peak.

A non-magnetic trolley had been built at RAE by modifying the one used for UK3 in the previous RAE test facility. This trolley allowed the spacecraft to be mounted with the z axis horizontal or vertical, enabling measurements to be made in each of the three axes. However, change from one orientation to another was made by removing the spacecraft from the trolley and remounting it. This procedure took place in the vehicle assembly building (S1) shown in Fig 5. The trolley and spacecraft were then man-handled to the test track for the next measurement. Therefore polar plots were impossible; measurements had to be restricted to the spacecraft axes. Otherwise the procedure was similar to that used at the RAE. The magnetometers were set to zero with the spacecraft at the far end of the track and the readings were taken when it was at the test position between the magnetometer probes. The probe separation was reduced to improve the signal to noise ratio at the expense of making the multipole effects more pronounced. The RAE results at two ranges showed that the inverse cubic law for magnetic field as a function of distance from the spacecraft was valid. Therefore, the figures obtained at San Marco were scaled accordingly and compared directly with the RAE values for measured magnetic field on each axis. When making the z axis measurement, the construction of the trolley made it convenient to use asymmetric magnetometer probe spacings.

The drift and background noise made operation of the two magnetometers used
047 impossible on their most sensitive range. This had the effect of degrading the resolution and calibration error to ±2 gammas in each case. The probe separation

distance measurement was assessed as accurate to ±20 mm, which was equivalent to a field indeterminancy of ±1 gamma. As the tests were conducted in the Earth's field, there was also an uncertainty due to the induced moment which the RAE measurements showed to be equivalent to ±2 gammas. These tolerances have been deliberately assessed pessimistically to minimize the chance of claiming a change had occurred in the moment, which was in fact spurious. The assessment of the results of the tests was carried out jointly with the Project Officer and the Project Scientist.

B.2 Preliminary test on arrival

The day after the spacecraft arrived on San Marco, immediately after it had been unpacked, a quick and crude field check was carried out. The spacecraft was hung from an overhead hoist in the clean room with its z axis vertical. A polar plot of its xy plane field was obtained by rotating the spacecraft past a horizontal magnetometer probe. The z axis field was measured by placing a vertical probe on the floor beneath the spacecraft, which was then lowered until a suitable reading was obtained and the separation was measured.

The clean room was a welded steel structure and rather confining for these tests. The proximity of the steel certainly distorted the fields produced, though the building construction at least shielded 90% of the Earth's field. The need to perform this test quickly to avoid unnecessary checks to the overall spacecraft programme and the other problems mentioned made no attempt at refinement worthwhile. The test confirmed that the magnetic state was substantially the same as it had been at the RAE and that was all that had been required of it.

B.3 Other tests at San Marco

The final magnetic surveys of the spacecraft before the heat shield was fitted to the launcher, were carried out by measuring the field at known points with a hand held probe. The results were compared with a similar survey carried out in the clean room after the main magnetic tests. They indicated that there had been no change.

The DCM was given a final calibration check in the clean room. The small physical size of the DCM in relation to the spacecraft and the fact that ample time was available to set up an accurate test allowed results to be obtained which were as accurate as those produced at the RAE. The calibration chart, which agreed with all previous calibrations, is shown in Fig 3.

As a last precaution, the magnetic state of the flight spare experiments B and D was checked. Again, their small physical size and a relaxed timescale allowed a measurement to be made which confirmed that there had been no change, although the test was not conducted to the same standards of accuracy as at RAE.

Appendix C

MAGNETIC SURVEY OF SAN MARCO PLATFORM

C.1 Requirement for a survey

Section 6 of this Report refers to the magnetic survey carried out at the San Marco platform to discover whether useful magnetic measurements of the spacecraft could be made.

The San Marco launch platform is very similar to an offshore oil drilling platform. It lies 5 km off the Kenyan coast at Ngomeni near Malindi. It is built almost completely of steel with a deck consisting of welded steel plates. Obviously there were going to be considerable perturbations of the Earth's magnetic field. Before any measurements could be made on the spacecraft the ambient magnetic field had to be mapped in some detail to establish that those distortions would not preclude a realistic assessment of the magnetic state of the spacecraft.

C.2 The survey

Fig 5 shows the area of the deck which was surveyed and the grid reference system based on two metre squares used to establish surveying points. At each grid line intersection the horizontal and vertical components and the horizontal direction of the ambient field were measured at heights of 1.0 and 1.5 m above the nominal deck level which was taken as the concrete surface outside the vehicle assembly building (S1). The height range encompassed the points that the centre of the spacecraft would be at when mounted on its magnetic test trolley.

Measurements were also made of the background noise level and its likely effect on the spacecraft measurements.

C.3 Results

Fig 6 shows the horizontal direction of the ambient field. The gap defined by grid lines A, D, 4 and 7 was occupied by a mobile crane parked in the position and attitude it would have during the spacecraft tests. The results show that in the area bounded by lines 3 and 7 the ambient field was sufficiently uniform in direction for induced effects to be acceptable. Figs 7 and 8 show the magnitudes of the horizontal and vertical components of the ambient field. They show that the area of uniform direction corresponds with an area over which the magnetic gradients are low.

The short term random variation of the ambient field over a few seconds was about ±5 gammas. The longer term drift varied but was typically a few tens of gammas over several minutes. The variation between a pair of differential probes 14 m apart, as used for the spacecraft tests was about ±2 gammas. With the differential probes together in the same holder the variation was ±0.5 gammas. A number of standard magnets of known moment were used to confirm that the measurement accuracy would not be worse than ±2 gammas.

An unexpected variation in the ambient field observed was the occasional occurrence of a square wave lasting a few minutes with an amplitude typically of 50 gammas. The change was observed while using differential probes and therefore must have been a locally generated effect. A change in the Earth's field would not be apparent unless a total field measurement was made. The changes were apparent simultaneously on three independent though identical magnetometers so an instrument fault can be virtually eliminated. Attempts to reproduce the event by switching on or off the heavy electrical machinery and generators on San Marco and the neighbouring Santa Rita tracking and control platform failed to show any correlation. The change had no more than a nuisance value. Even when it recurred during the magnetic tests on the spacecraft, the only outcome was a need to repeat one of a fairly large number of measurements. Therefore the matter was allowed to remain unresolved.

C.4 Other environmental effects

The other environmental conditions which could potentially have affected the tests were the heat, the humidity, the slight motion of the deck due to the waves and the wind. The magnetometers remained in the shade all the time and neither heat nor humidity had any apparent effect on them or on their probes. The deck motion was measured at about ±25 seconds of arc and correlated in time and magnitude with the variation observed between differential probes. The most serious problem was the constant wind of about 10 m/s which blew the probe mounts about. The problem was alleviated by the erection of wind breaks.

Appendix D

POST LAUNCH OBSERVATIONS

Ariel 5 has at the time of writing been operating successfully in orbit for 2 years. There have been no dramatic changes in its behaviour which suggest significant magnetic changes, though there have been unpredicted effects, probably of magnetic origin, which are not relevant to this Report.

The predicted magnetic moment at launch was -0.044 ± 0.176 μWb m, that is within the range -0.220 to $+0.132$ μWb m. Subsequently, it was discovered that the DCM required setting to level +8 to reduce the spin axis drift rate below the specified limit. This level corresponds to a DCM moment of $+0.217$ μWb m. In fact, this level caused a slight overcorrection of the drift rate, so the total spacecraft moment can be assumed to have been less than -0.217 μWb m. This is within the tolerance band allowed and suggests that the measurements made at San Marco were reliable and showed a real change. Tests conducted on the DCM in orbit suggest that its output may be significantly less than was measured in ground tests. The reason for this is not clear, but if it is true over the whole DCM range, the spacecraft moment may have been nearer the centre of the tolerance band.

Recently the DCM has required resetting to level +9, which implies a spacecraft moment change to -0.43 μWb m.

The author is grateful to Dr G.M. Courtier of the Appleton Laboratory, Science Research Council, for the above unpublished information.

Table 1

HISTORY OF UK5 MAGNETIC MOMENTS

State	Magnetic moment μWb m			
	M_x	M_y	M_z	Total
As received at RAE	+9.2	-21.5	+72.6	76.3
Post exposure to 2000 A/m	+2.1	-21.8	+72.7	75.9
Post demagnetization 4000 A/m, 1%, 2 Hz	+2.6	-12.1	+31.8	34.1
Post demagnetization 4000 A/m, 1%, 0.5 Hz	+3.3	-11.7	+27.3	29.9
Post demagnetization 4000 A/m, 1%, 0.1 Hz	+3.9	-11.8	+24.7	27.7
Experiments B and D removed	+0.42	-0.44	-1.30	1.44
Post demagnetization 4000 A/m, 1%, 2 Hz	-0.29	+0.07	+0.11	0.32
Experiments B and D compensated and re-fitted	-0.36	+0.11	+0.14	0.40
Baseline measurement	-0.43	+0.03	-0.03	0.43
On return to RAE	-0.36	+0.04	-0.03	0.36
Trim magnet fitted: as left RAE	-0.28	+0.08	+0.04	0.29
As measured at San Marco	-0.28	+0.08	+0.29	0.41
After changing compensating magnet: launch value	-0.28	+0.08	-0.05	0.30
Stray magnetic moment	+0.25	-0.03	+0.01	0.25
Estimated total moment at launch	-0.03	+0.05	-0.04	0.07
Induced east-west moment in 16 A/m field				
East-west field	+0.31	+0.23	+0.38	
North-south field	0	0	-0.04	
Vertical field	+0.04	0	-0.03	

Table 2

HISTORY OF EXPERIMENT B FLIGHT MODEL PERMANENT MAGNETIC MOMENT

State	Permanent magnetic moment μWb m			
	M_x	M_y	M_z	TOTAL
As removed from spacecraft	2.3	14.7	14.6	20.8
After repeated demagnetization from 4000 A/m	2.0	10.0	10.9	14.9
After demagnetization from 8000 A/m	0.5	1.0	2.1	2.4
After demagnetization from 12000 A/m	0.09	0.70	1.06	1.27
Before leaving RAE after further demagnetizations	0.6	1.9	4.5	4.9
On return to RAE	-0.16	-1.9	+4.4	4.8
After demagnetization from 12000 A/m	+0.16	-0.08	+3.5	3.5
After fitting compensating magnet: as refitted to spacecraft	+0.05	-0.06	0	0.08

Table 3

HISTORY OF EXPERIMENT B FLIGHT SPARE PERMANENT MAGNETIC MOMENT

State	Permanent magnetic moment μWb m			
	M_x	M_y	M_z	TOTAL
As received at RAE	-1.10	-17.8	+60.5	63.1
After demagnetization from 12000 A/m	+0.59	-0.91	-0.05	1.09
After demagnetization from 4000 A/m	+0.49	-0.09	+1.32	1.41
On return to RAE	+0.38	-0.09	+1.14	1.21
After fitting compensation magnet	+0.39	-0.09	-0.13	0.42
After vibration	+0.41	-0.09	-0.13	0.44
After fitting new counter	+0.28	+0.49	-0.33	0.65
After several demagnetizations (trim magnet removed)	+0.38	+0.53	+0.73	0.98
Compensation magnet refitted	+0.29	+0.26	-0.11	0.40

Table 4

HISTORY OF EXPERIMENT D FLIGHT MODEL PERMANENT MAGNETIC MOMENT

State	Permanent magnetic moment μWb m			
	M_x	M_y	M_z	TOTAL
As removed from spacecraft	9.0	0.52	11.4	14.5
After demagnetization from 4000 A/m	8.5	0.31	10.7	13.7
After demagnetization from 8000 A/m	0.30	0.54	3.3	3.4
Before leaving RAE after further demagnetization	0.82	0.31	3.1	3.2
On return to RAE	+0.74	+0.30	-7.0	7.0
After demagnetization from 12000 A/m	-0.06	-0.09	+2.0	2.0
After fitting compensating magnet: as refitted to spacecraft	-0.24	0	-0.05	0.25

Table 5

HISTORY OF EXPERIMENT D FLIGHT SPARE PERMANENT MAGNETIC MOMENT

State	Permanent magnetic moment μWb m			
	M_x	M_y	M_z	TOTAL
As received at RAE	+9.8	+0.43	+42.7	43.8
After demagnetization from 12000 A/m	+2.5	+0.13	-0.13	2.5
After demagnetization from 12000 A/m, y and x axes only	-0.82	+0.10	-0.12	0.83
After fitting compensating magnet	-0.33	+0.11	-0.11	0.36

Table 6

COMPARISON BETWEEN MAGNETIC FIELDS MEASURED AT RAE WITH THOSE AT SAN MARCO

Axis west	Probe	Measured magnetic fields (gammas)			
		At San Marco	San Marco scaled to 1.7 m	At RAE at 1.7 m	Change
+z	1	+42	+17	+9	+8
+z	2	-7	-7	-16	+9
+x	1	-22	-15	-15	0
+x	2	+4	+3	-2	+5
-y	1	-14	-10	-9	-1
-y	2	-8	-5	-3	-2

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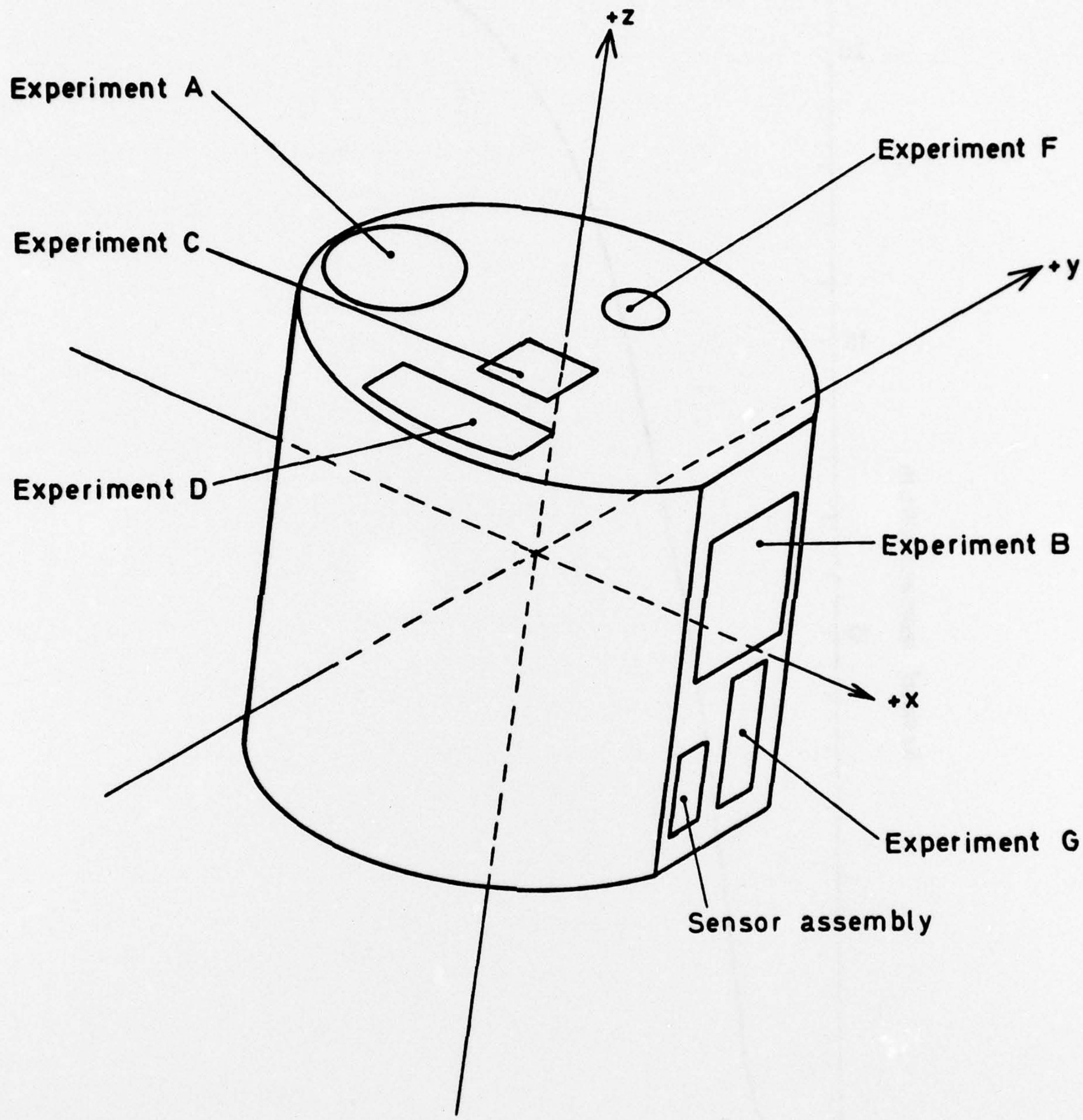

Fig 1 UK5 system of axes

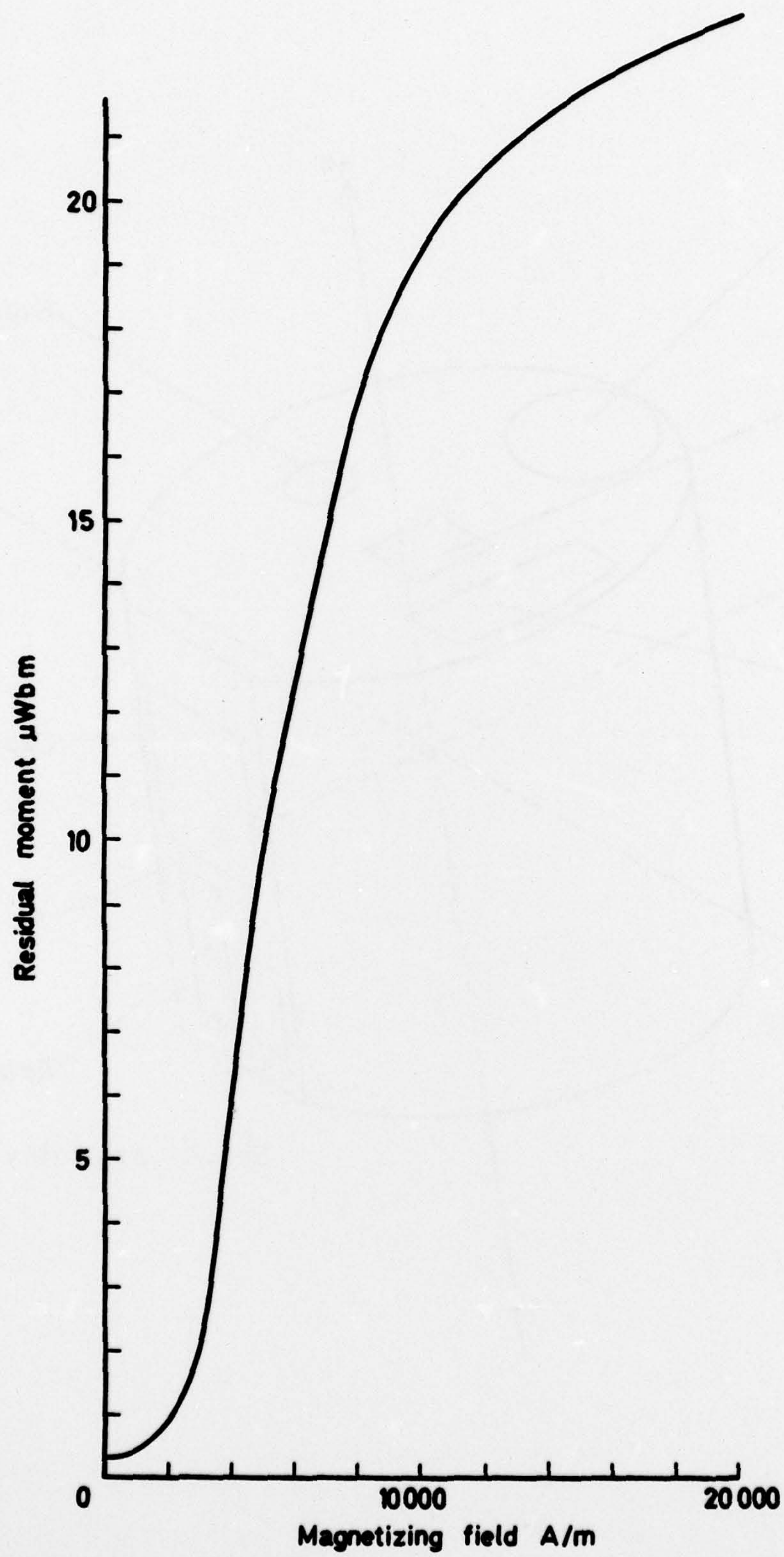

Fig 2 Residual magnetic moment after exposure to a magnetizing field for spare experiment B and D type counter body

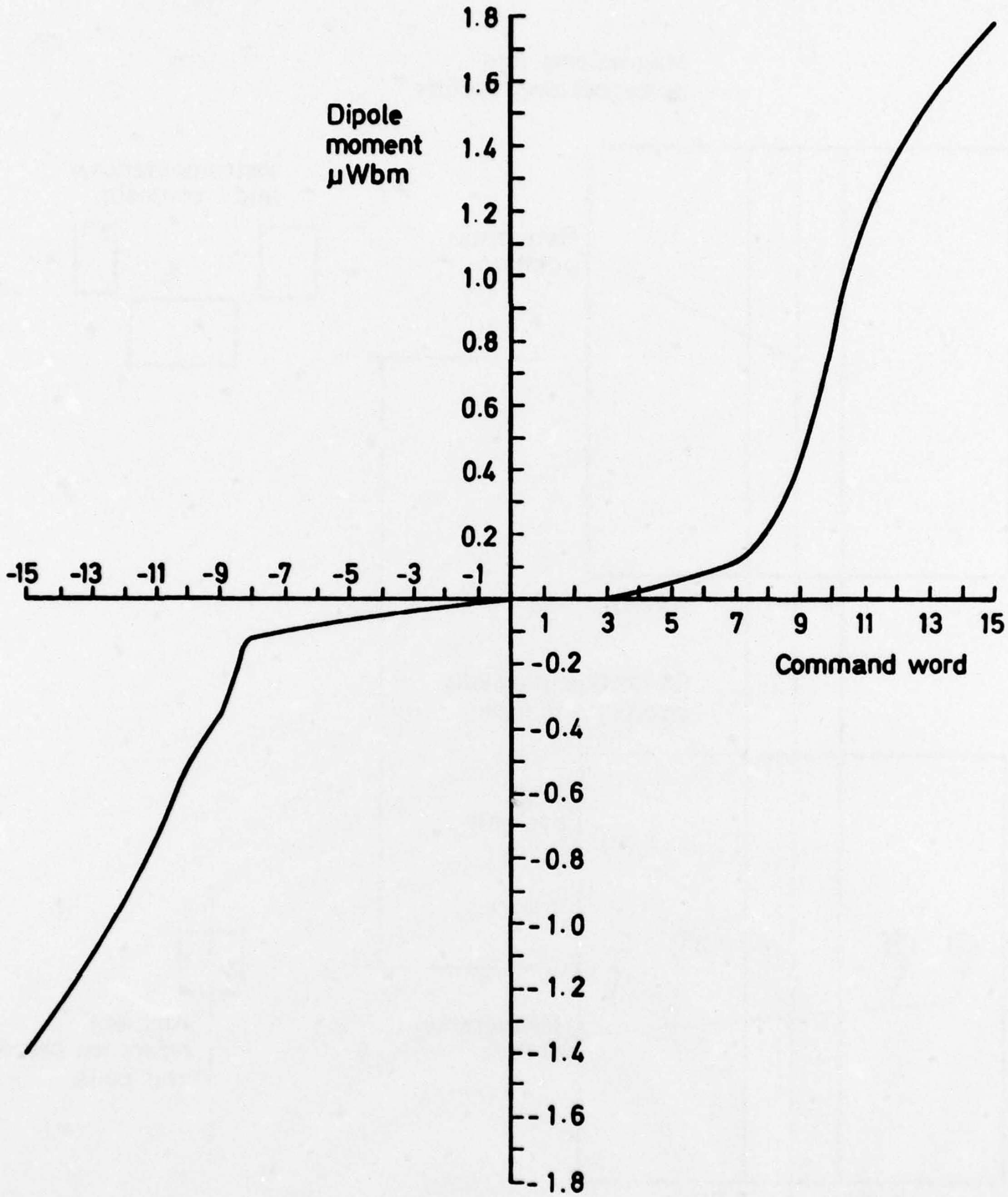

Fig 3 UK5 DCM characteristic

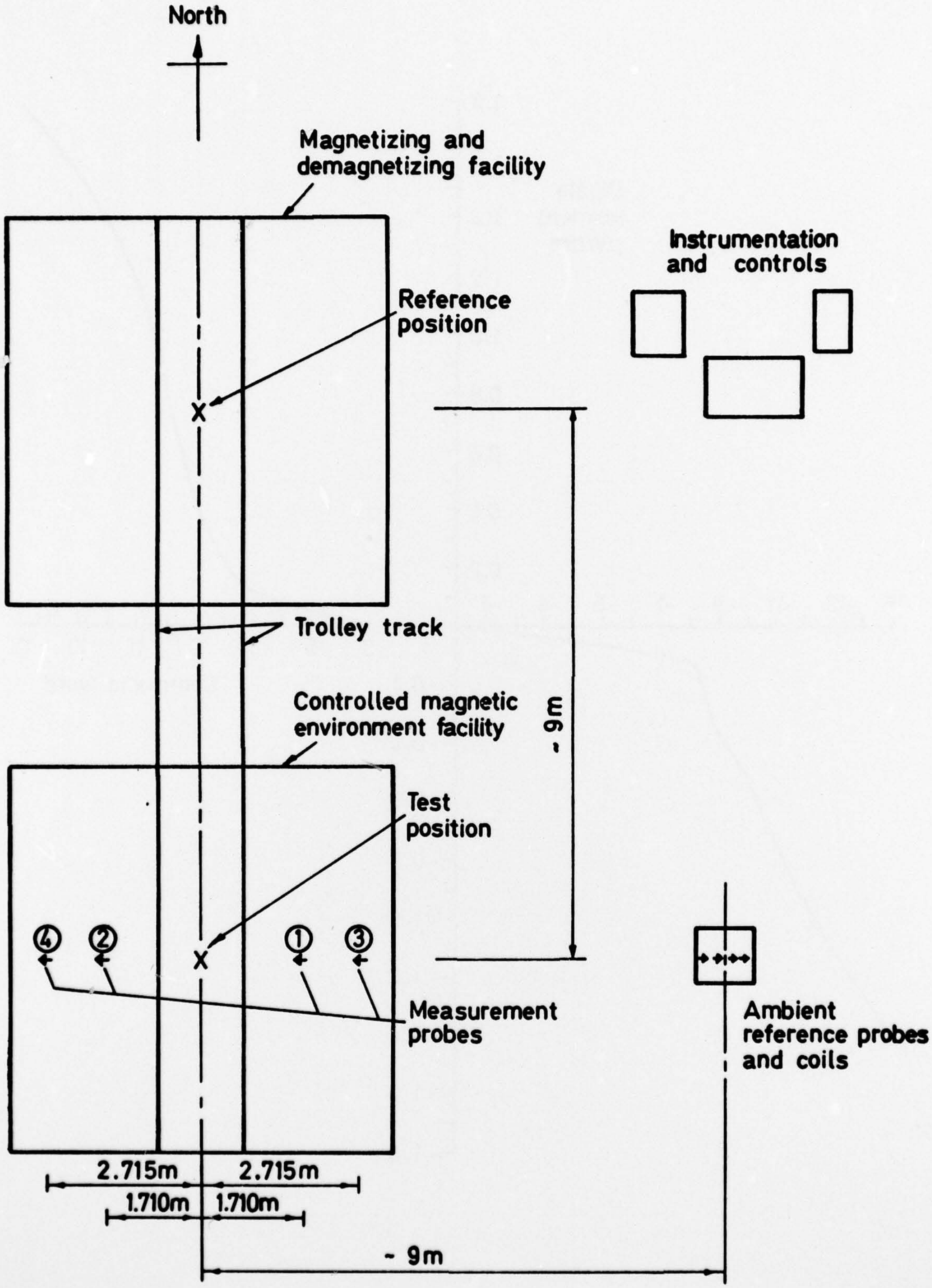

Fig 4 Layout of RAE magnetic test facility

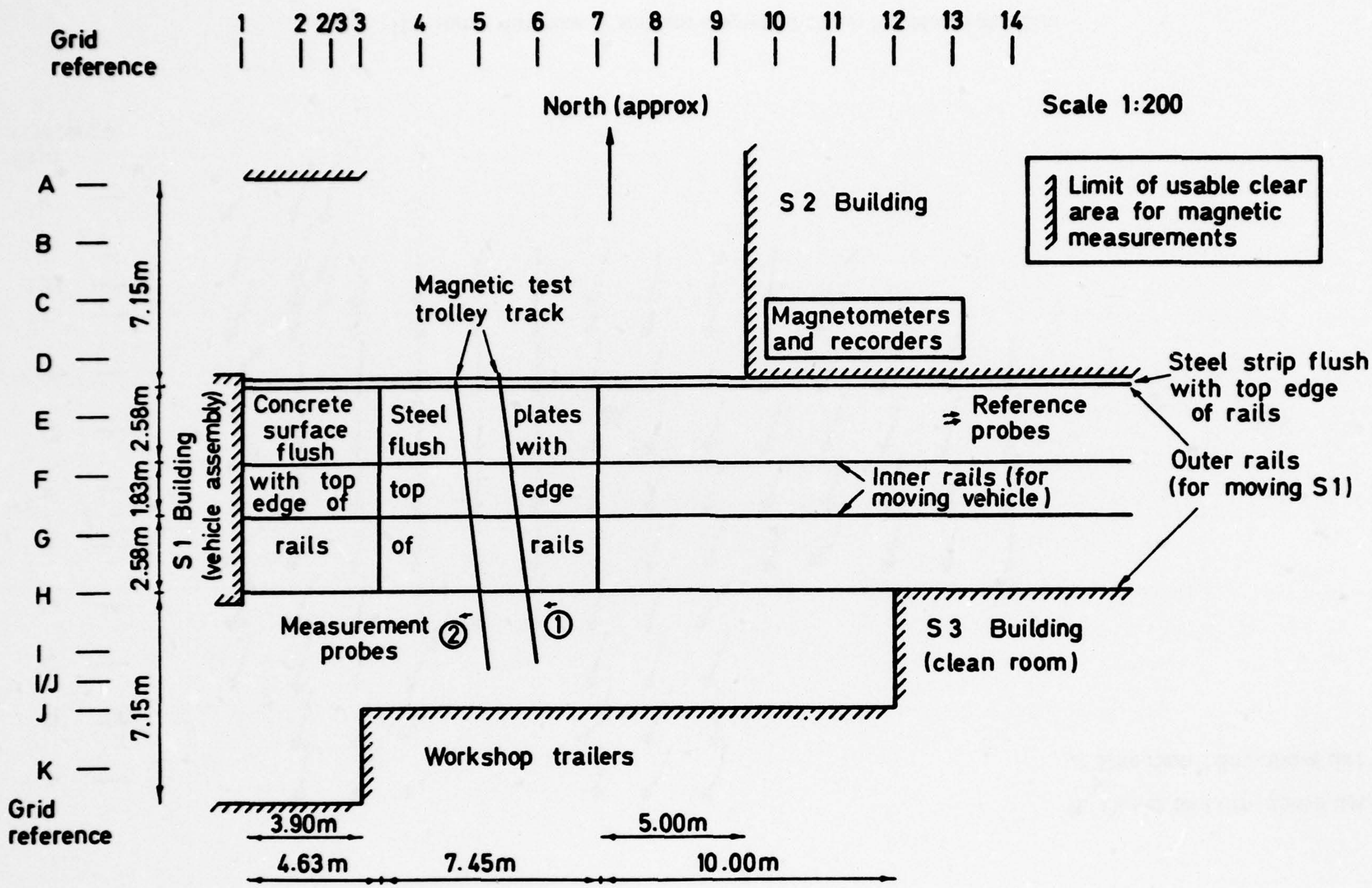

Fig 5 San Marco platform – magnetically surveyed area

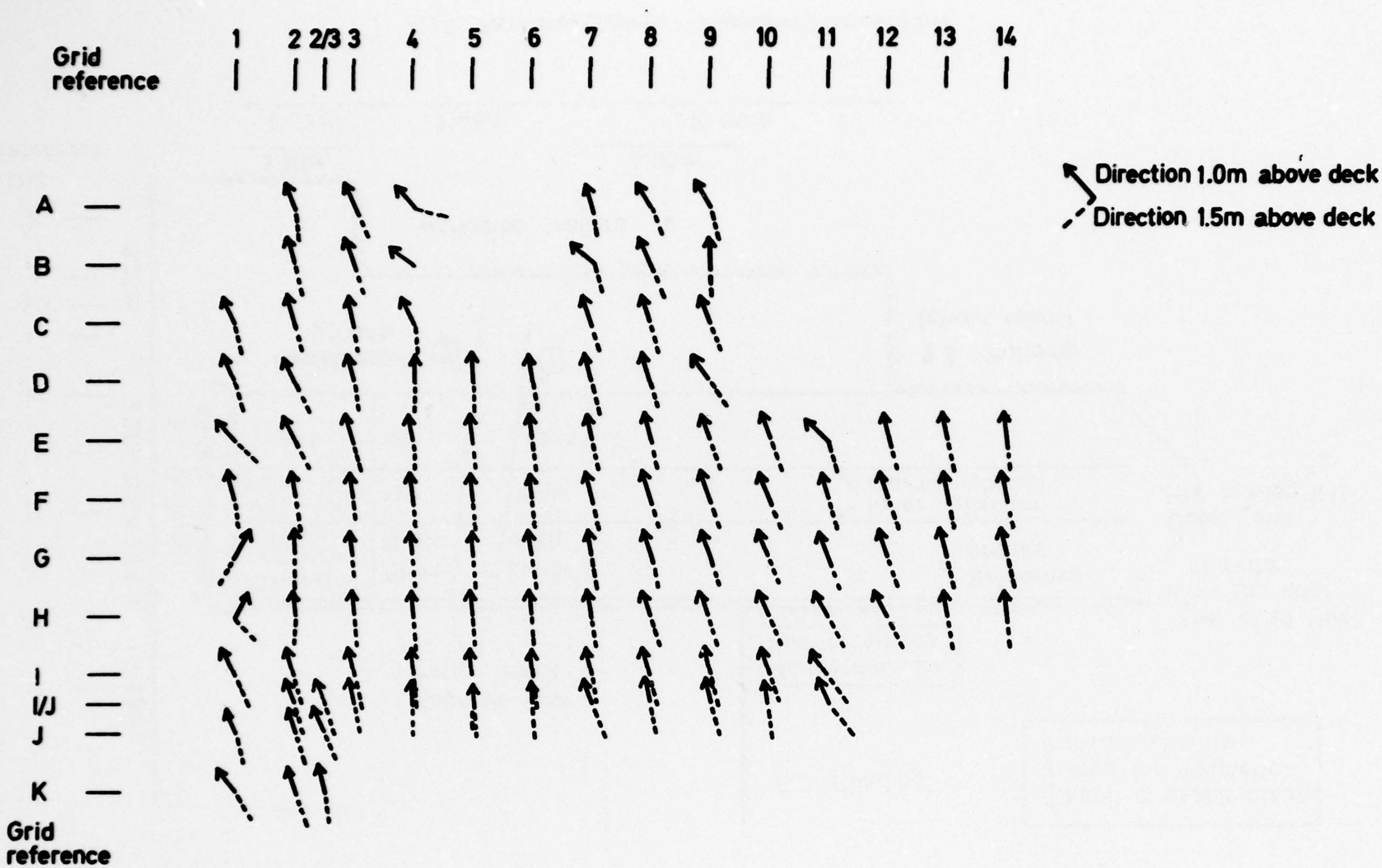

Fig 6 Horizontal direction of ambient magnetic field on San Marco platform

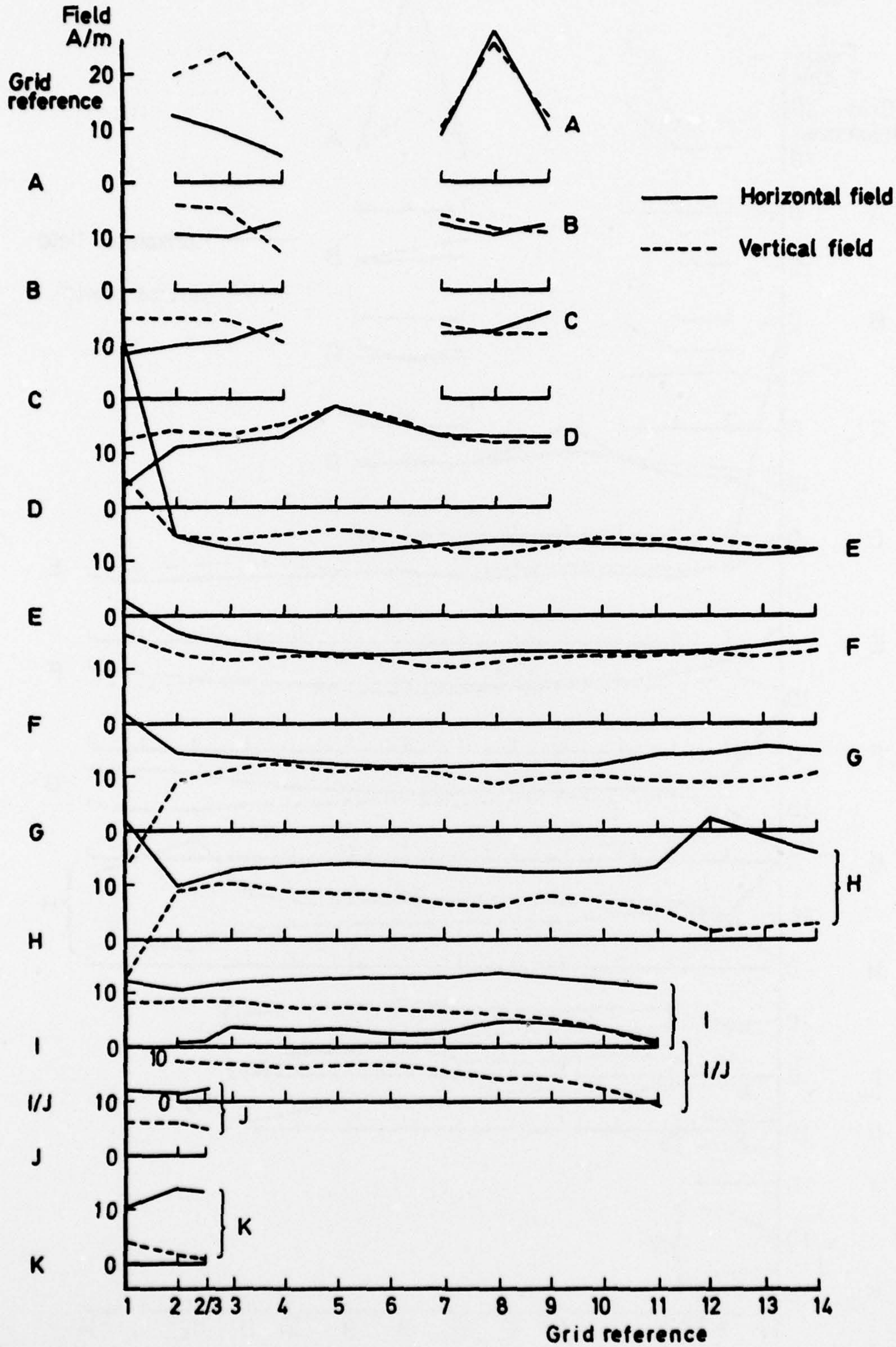

Fig 7 Magnitude of ambient magnetic field strength on San Marco platform 1.0 m above deck

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Fig 8

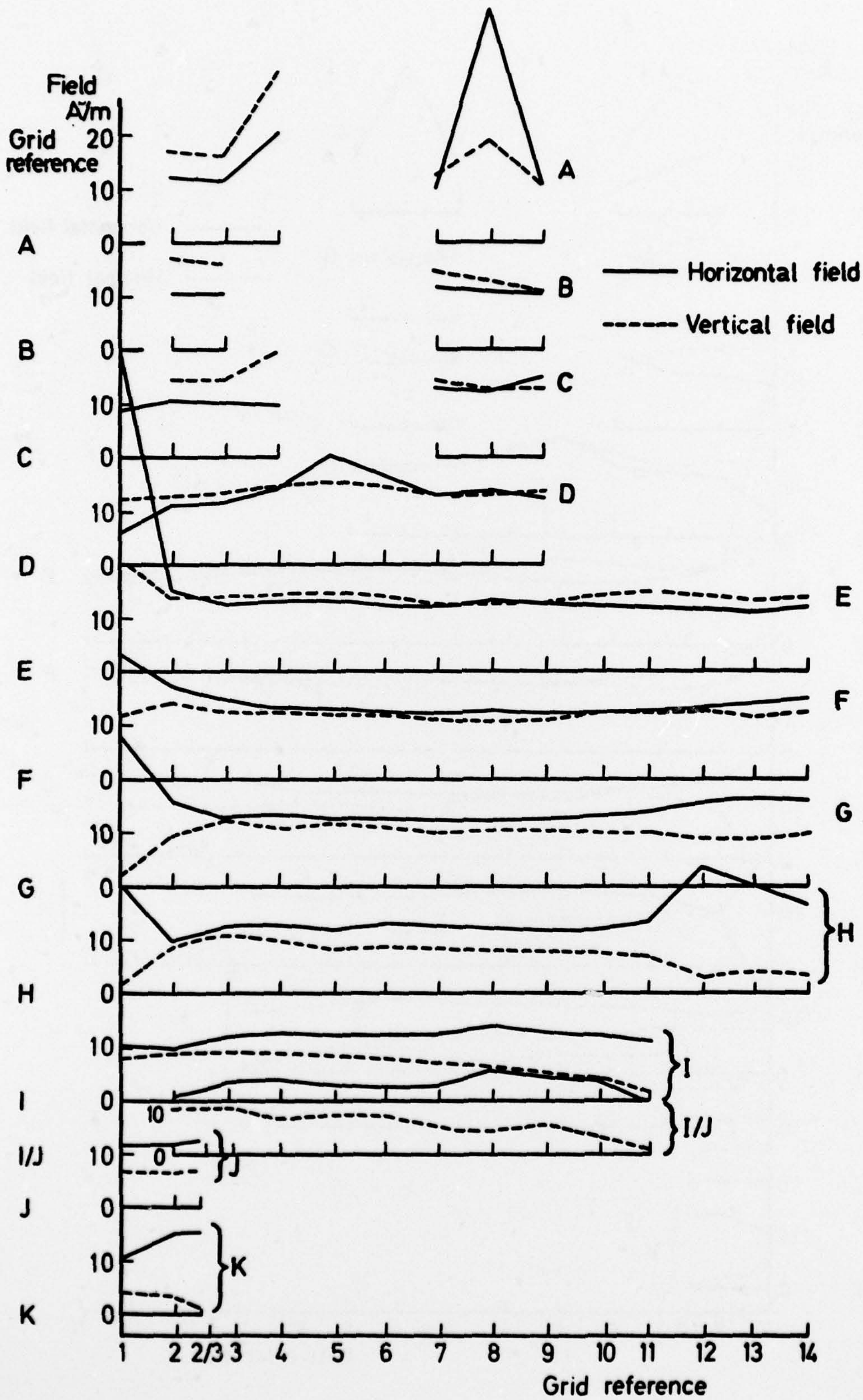

Fig 8 Magnitude of ambient magnetic field strength on San Marco platform 1.5 m above deck

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REPORT DOCUMENTATION PAGE

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1. DRIC Reference (to be added by DRIC)	2. Originator's Reference	3. Agency Reference	4. Report Security Classification/Marking
	RAE TR 77047	N/A	UNCLASSIFIED

5. DRIC Code for Originator	6. Originator (Corporate Author) Name and Location
850100	Royal Aircraft Establishment, Farnborough, Hants, UK
5a. Sponsoring Agency's Code	**6a. Sponsoring Agency (Contract Authority) Name and Location**
N/A	N/A

7. Title **The magnetic testing of the UK5 spacecraft**

7a. (For Translations) Title in Foreign Language

7b. (For Conference Papers) Title, Place and Date of Conference

8. Author 1. Surname, Initials	9a. Author 2	9b. Authors 3, 4	10. Date	Pages	Refs.
Lodge, D.W.S.			March 1977	37	9
11. Contract Number	**12. Period**	**13. Project**	**14. Other Reference Nos.**		
N/A	N/A	UK5	Space 524		

15. Distribution statement
(a) Controlled by – [redacted]
(b) Special limitations (if any) –

16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

Magnetic testing. UK5. Ariel 5.

17. Abstract

UK5 arrived for magnetic testing with an unexpected and excessive magnetic moment. The source of the moment was identified as the counter bodies of experiments B and D. This Report describes the work carried out to bring the moment within its specified limits. A great deal of unprogrammed activity was required to do so including the development of tests to confirm the eventual magnetic stability of the spacecraft. In particular, unscheduled and detailed magnetic testing was carried out at the launch site under highly adverse conditions.

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